30 years of forest hydrology changes at Coalburn: water balance and extreme flows

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Abstract

The Coalburn experimental catchment, located in the Kielder Forest in northern Britain, was established in 1967 to study the hydrological impacts of upland coniferous plantation forestry. Results of 30 years' study (1967–96) are presented; they cover the transformation of the catchment from rough grazing through drainage and planting with conifers in 1972–73 and the subsequent forest development to canopy closure. In the early years of forest growth, the pre-planting forestry drainage dominated the hydrology and the observed changes were quite different from those normally associated with forestry; catchment evaporation was reduced, stream stormflow response times were shortened and dry weather baseflows were enhanced. These effects were sustained for an unexpectedly long period—up to one half of the forest plantation cropping cycle—before being reversed by the increasing influence of the growing forest. These results indicate that significant areas of young plantation forests may function hydrologically in ways very different from what is generally assumed from studies of mature forests. For large plantations, a mixed age forest structure may have hydrological as well as environmental advantages.

Introduction

The uplands of Britain constitute only about 20% of the land area but provide about 50% of the water supplies. They also contain the greater part of the nation's commercial plantation forests. The need to understand the impact of this land use on water resources has been of particular concern and was a major factor in the creation of the UK's Institute of Hydrology. The Institute's work at Plynlimon in mid-Wales comparing the hydrology of established forest with grassland is well known (e.g. Neal, 1997), but did not deal with tree establishment. The smaller Coalburn study described here was originally intended to deal just with the early hydrological impacts of afforestation, but its research programme has expanded and developed into a continuing study of forestry growth effects on streamflow, providing a unique British study of afforestation from planting through to canopy closure, and onwards to the felling of the crop around 2020. It has become Britain's longest running research catchment.

In addition to the long term measurement of the main components of the water balance, shorter term process studies have been conducted. These include forest canopy interception losses and cloud water deposition, soil water movement and water chemistry. Further details are available in Robinson et al (1998). Particular aspects are also described elsewhere, including erosion (Robinson and Blyth, 1982), water quantity (Robinson, 1986) and water chemistry (Mounsey, in prep.).

Site and instrumentation

The Coalburn catchment was selected to represent the areas of upland Britain where commercial forestry is concentrated. The tree species planted, the waterlogged peaty soil types, and the need for extensive ground cultivation and drainage to aid tree establishment are typical of many upland catchments. Coalburn is situated within the Kielder Forest, in north west England which is the largest man-made forest in Northern Europe. The study area (Fig. 1) is a 150 ha headwater tributary of the river Irthing. It is underlain by glacial boulder clay deposits up to five metres thick and the catchment is considered to be watertight. The ground has generally low slopes and the soils consist of blanket peat (0.3–3 m thick) and peaty gleys. The mean annual precipitation is about 1350 mm, distributed fairly evenly through the year.

The first full year of study was 1967 when the study area comprised short vegetation such as *Molinia* grassland and peat bog species including *Eriophorum*, *Sphagna*, *Juncus* and *Plantago*. After a five year pre-forestry 'baseline' period of hydrological monitoring, the catchment was

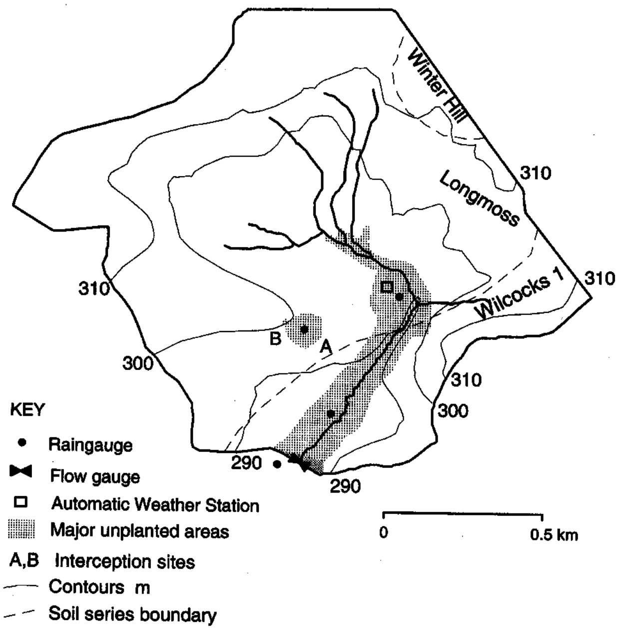

Fig. 1. *Coalburn catchment, showing its location and instrumentation.*

plough drained in 1972 and planted in the following year with coniferous species, principally Sitka spruce (*Picea sitchensis*). Pre-planting drainage on wet, peaty sites is a widespread practice in northern Europe. At Coalburn this comprised open ditches, termed 'plough furrows' by foresters, about 0.5 metres wide and 4.5–5 metres apart. Initially 0.8–0.9 metres deep, they are now only about half that depth due to colonisation by vegetation, sedimentation and the accumulation of tree litter. The drainage plough deposited the excavated material to either side in continuous ridges. Young trees about 0.2 m tall were planted at about 1.5–1.7 metres spacing on these ridges. In total, 90% of the study catchment was planted. By the end of 1996, the trees had grown to about 10 metres tall and the forest canopy had closed. The forest growth (Yield Class 12 m^3 ha^{-1} yr^{-1}) is fairly typical of upland areas.

During the baseline period, precipitation was measured at 13 sites across the moorland. Analysis of the data confirmed that, due to the gentle topography, there was little spatial variation, and four sites were chosen for permanent instrumentation. Large areas were left unplanted around each of these raingauges to ensure that the trees did not interfere with the homogeneity of the precipitation records. Independent confirmation of this was obtained by comparison with records from Meteorological Office raingauges outside the forest (Robinson et al., 1998).

Since 1971, an automatic weather station has provided onsite meteorological measurements for the calculation of Penman potential evaporation. This is a valuable 'datum' to distinguish between the influences of climatic variability and land use change when interpreting changes in the catchment water balance over time. Prior to 1971, and subsequently for periods of missing data and for data consistency checks, Penman estimates have also been obtained from the nearby Eskdalemiur Observatory operated by the UK Meteorological Office. Streamflow at the catchment outlet is measured with a weir which has its foundations sunk into the underlying shale bedrock to prevent underflow. Streamflow discharges are checked by current meter gaugings.

Results and discussion

This paper summarises some of the main findings from the period 1967–96. This covers the initial 5-year baseline period for the moorland catchment, through its drainage in 1972 and forest planting in 1973 up to the end of 1996, when the trees had attained a closed canopy over most of the catchment.

WATER BALANCE

A comparison of the annual precipitation and streamflow totals is given in Fig. 2. For a given annual precipitation, there was a marked increase in annual streamflow *after* the afforestation. The amount varied considerably from year to year, but was typically in the range +50 to +100 mm. This increase of over 10% was quite contrary to the bulk of published results on forest hydrology; almost all show a significant *reduction* in flows due to forestry (e.g. Bosch and Hewlett, 1982). The forestry drainage works released huge quantities of sediment which prevented streamflow measurements in the winter of 1972/73, so that flows for parts of those two years have had to be estimated from the rainfall records. Table 1 summarises the water balance in 5-year blocks, to reduce the effect of annual storage changes. In the first period following ploughing, the catchment evaporation losses (precipitation minus streamflow) reduced by an equivalent of almost 100 mm

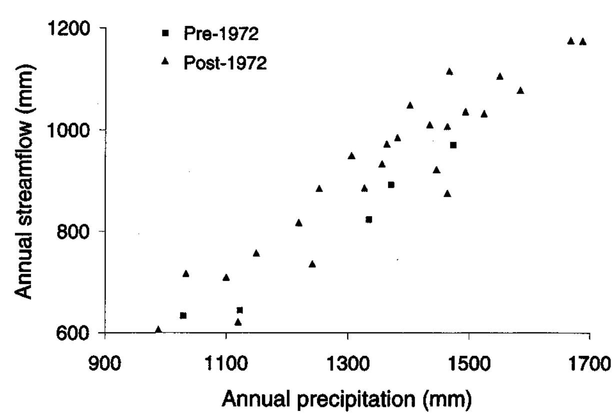

Fig. 2. *Comparison of annual precipitation and streamflow totals (mm) showing an increase in flows after drainage in 1972.*

Table 1. Water balance of the Coalburn catchment showing five-year average annual depths (mm).

Period	Precipitation (P)	Discharge (Q)	Losses (P-Q)	Penman (PE)	Change (PE-(P-Q))
Before ploughing					
1967–71	1266	793	472	433	–39
After ploughing					
1972–76	1149	766	383	435	52
1977–81	1421	995	426	437	11
1982–86	1445	1025	420	442	22
1987–91	1415	998	416	439	23
1992–96	1370	846	524	454	–70

yr^{-1}. This could not be attributed to changes in the surface area of the catchment resulting from the ploughing because, at the start of the study, a double boundary ditch had been cut around the catchment (Robinson et al., 1998). Successive ground surveys have confirmed its integrity. A long term increase in total flows from land after drainage has been identified in a number of drainage studies (e.g. Green, 1970; Seuna, 1980), irrespective of any short-term dewatering of waterlogged soils. This may be attributed to a general lowering of the water table, reducing evaporation losses, and suppression of transpiration from the bare soil of the plough drains and the overturned ridges. At Coalburn, the open drains and overturned turf ridges comprised about 20% of the total surface area of the catchment.

Over time, as the bare soil in the drains became colonised with vegetation, and as the young forest plantation became established and grew, the evaporation losses (precipitation minus streamflow) have increased (Robinson et al., 1998). This can be seen most clearly when they are compared with estimates of the Penman potential rate. Figure 3 shows the annual difference between actual losses and Penman values. Initially evaporation from the moorland vegetation was about 9% higher than the Penman estimates for short grass. This is in line with previous work which showed that the Penman equation underestimates evaporation at windy sites (Thom and Oliver, 1977). Although the amount (~ 40 mm yr^{-1}) is small, it shows that studies which compare measured forest evaporation with Penman estimates of losses from grass may in fact overestimate the forest's impact upon the water balance by an equivalent amount.

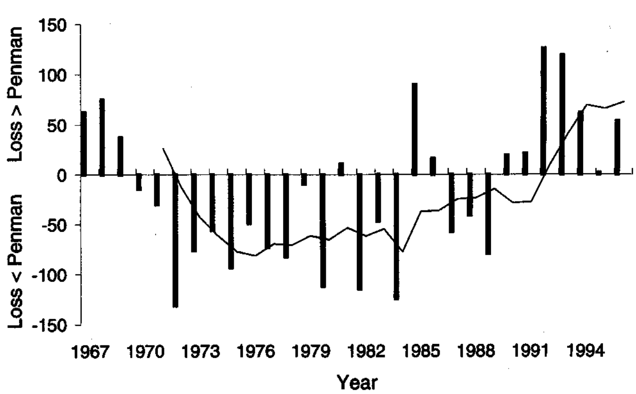

Fig. 3. *Changing pattern of actual evaporation losses (precipitation minus streamflow) compared with the Penman potential evaporation values (mm).*

The drainage in 1972 caused a great reduction in apparent evaporation losses, partly in consequence of the short-term release of water from the peat, which was observed at the time. Thereafter the losses have increased steadily as shown by the rising line of the 5-year moving average curve (Fig. 3). The surprising feature is that it has taken about two decades for evaporation losses to exceed those from the original moorland.

With cropping cycles of about half a century, evaporation losses have been suppressed for over one-third of the expected commercial life-span of the forest.

Interception studies

A major reason reported in the literature for the greater evaporation losses from forests than from shorter vegetation is the higher interception losses from forests due to their greater aerodynamic roughness (e.g. Calder, 1990). Forest interception losses at Coalburn were measured using large plastic sheet gauges (Calder and Rosier, 1976). Replicated gauges (25 m^2 and 44m^2) were installed at each of two sites with trees of the same age but different heights (Robinson et al., 1998). The two smaller sheets contained 7 tree stems and the two larger sheets 14 or 15. Over the 31-month period, May 1994 to December 1996, the trees grew about 1 m per year; the shorter trees increased in height from 7 to 9 m whilst the taller trees grew from 9 m to 11 m. The sheets collected throughfall, drip and stemflow and the runoff was recorded using large tipping bucket recorders. The net rainfall was compared with the gross rainfall recorded at a ground level raingauge in an adjacent unplanted area.

The interception losses as a proportion of rainfall varied through the year, being highest in the summer and lowest in the winter. There was evidence of an increase in losses over time, associated with tree growth. In the first year, May 1994 to May 1995, the interception losses were 21.1% of gross rainfall from the shorter trees and 23.1% from the taller trees. For the whole period to December 1996 the interception losses for all sheets were higher, averaging 24.9% from the shorter trees and 27.7% from the taller trees. These interception ratios are lower than values elsewhere in the UK for similar climatic conditions where values of about 35% (Calder and Newson, 1979; Calder, 1990) were generally obtained for sites with more mature trees than those at Coalburn.

The picture that emerges of low forest interception losses, which increase with tree height (between sites and over time at each site) is compatible with the catchment water balance studies showing year on year increases in evaporation losses.

Transpiration

Consideration of the current water balance (Table 1), with the known net interception loss, and the forest coverage indicates a residual amount of only about 150 mm yr^{-1} for forest transpiration. This is much lower than the values of about 300–350 mm yr^{-1} widely reported in the literature (cf. Roberts, 1983), although there is some supporting evidence of low forest transpiration rates from other upland catchment studies in Britain (Hudson et al., 1997; Hall and Harding, 1993). Accordingly, measurements of sapflow have been started using the heat pulse velocity method, in conjunction with meteorological measurements and soil water contents. It is hoped this will provide a direct estimate of transpiration losses and will also indicate whether forest transpiration is being limited by environmental factors, such as low temperatures. If transpiration rates are restricted, then this finding would have implications for other upland forested areas.

Initial results indicate that the sapwood layer of the trees (*Picea sitchensis*, 25 years old) is only about 20 mm thick compared with values of 12–50 mm generally reported in the literature for temperate zone forests (Desch and Dinwoodie, 1996).

Table 2. Average number of storm discharge peaks per year above specified thresholds ($m^3\ s^{-1}$). Frequencies significantly greater than before the drainage in 1972 are indicated by * (α = 0.10 level).

Threshold ($m^3\ s^{-1}$)	>0.9	>1.0	>1.2	>1.5	Mean annual peak ($m^3\ s^{-1}$)
Period					
1967–71	4.6	3.0	2.4	1.6	1.97
1974–83	6.9*	5.7*	3.8*	1.7	2.33
1984–90	7.0*	4.7	2.7	1.3	2.20
1990–96	5.3	4.2	3.2	1.2	1.87

EXTREME FLOWS

Forests are widely reported in the scientific literature as altering flow regimes; peak flows are generally reduced and response times lengthened; changes to low flows are less clear, with conflicting reports of increases in some studies and reductions in others.

Peak flows

The flow data for Coalburn were examined to abstract a series of independent hydrograph peaks above a range of threshold flows (Table 2). An apparent increase in the frequency of peak flows, particularly the smaller ones, following the drainage indicates that the plough drains provided impermeable surfaces and efficient flow paths for the rapid movement of surface water during storms (David and Ledger, 1988). The annual maximum floods increased by about 15% following drainage but, due to the large variations between individual years, this increase was not statistically significant.

It is difficult to draw definite conclusions because the occurrence of peak flows is very sensitive to the number and magnitude of rainstorms. For this reason, the events were then examined in more detail to determine changes in flood hydrograph shape, using the unit hydrograph technique to remove the effect of any differences in the storm rainfall profiles (Robinson et al., 1998). It was found that there were statistically very significant changes (α = 0.005) in the first decade following the drainage, with a shortening of the hydrograph rise times, and an increase in the unit hydrograph peaks. Figure 4 shows the changes for individual storms over the study period in the unit hydrograph time to peak. This was shortened from about 2.2 hours before ploughing to about 1.7 hours in the five years afterwards, and has increased steadily back to pre-drainage values. The increasing attenuation of flood hydrographs over time since the drainage accords with field observations that the drains became colonised by grasses and mosses and, more recently, with the growth of the trees they now hold large quantities of litter from needle fall. No clear pattern of changes in flood hydrograph volumes has emerged, although these may well decrease at least for small summer storms (below the threshold studied here) due to the higher forest interception losses.

Low flows

Low flows were characterised using the Baseflow Index (BFI). This widely used technique expresses the proportion of annual flow which occurs as baseflow according to a simple graphical separation procedure (Gustard et al., 1993). The average BFI doubled from only about 0.1 to 0.2 following the ploughing of Coalburn. A long-term increase in low flows after drainage has been widely found in studies and results from the greater depth of the artificial system than the natural channels it replaces or augments (Robinson and Rycroft, in press). The large

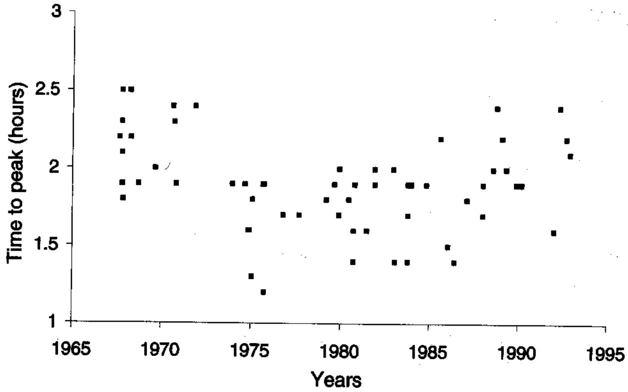

Fig. 4. *Changes in the unit hydrograph time to peak for individual storms (hours), showing an immediate reduction in response times following drainage in 1972, and a subsequent steady recovery.*

increase at Coalburn of 100% reflects the very low pre-drainage BFI to be expected for a small, impermeable headwater catchment. Much smaller proportional increases would be observed in larger basins with higher natural baseflow levels. For example, in a study of 1000 catchments (average size 300 km^2), the average BFI was about 0.5 (Gustard et al., 1993).

There has been a decline in the BFI values for Coalburn since the drainage, which may be due to the growth of the trees, but the rate of change is so slow that the pre-forestry value would be reached only around the year 2030, which is some 10-15 years after the scheduled date for the trees to be felled (Fig. 5). Thus, the increase in low flows seems to be effectively a permanent feature of managed plantation forest—at least for conditions similar to those at the study site.

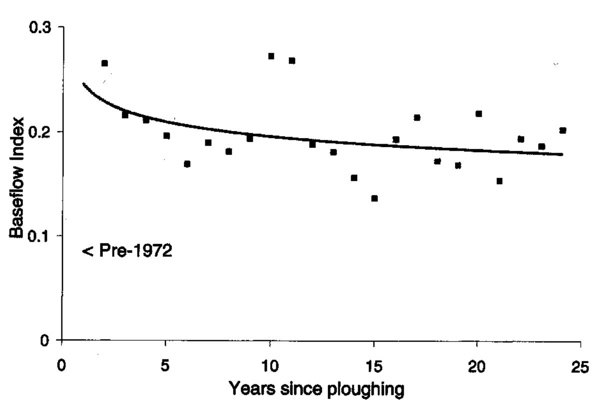

Fig. 5. *Decline in annual Baseflow Index values since afforestation. The pre-forestry level is shown. At current rates of change the BFI will remain above the pre-forestry level for the remainder of the cropping cycle.*

Implications

The study shows that managed plantation forestry can have hydrological effects that are very different to those expected on the basis of the results now published in the international scientific literature. Rather than reducing total streamflow, the immediate effect of the forestry at Coalburn was to increase the water yield as a result of the artificially increased drainage network. It was only several decades later that water yields fell below pre-forestry levels. Similarly, far from reducing peak flows, the afforestation increased them due to the network of artificial drains. Again, it was some years before a combination of deterioration of the drainage system and forest growth led to a reduction in peak flows in accordance with the 'classic' picture of forest hydrology. Low flows exhibited an even more extreme dependence upon the artificial drainage network with an effectively permanent increase in low flows, given the short cropping cycles of modern commercial forestry and the very slow rate of decline.

Conclusions

The Coalburn study has shown clearly for the first time the very different hydrological impacts of forestry drainage and forest growth. Some of the effects of drainage have been noted in shorter term studies, but this is the first time that their potentially long term nature has been demonstrated. The implication of the discovery that the impacts of the drainage are still detectable half-way through the cropping cycle is clear; possibly half of the coverage of Britain's upland forests may have hydrological effects that are the opposite of what had previously been thought, based on studies of more mature forests. The degree and longevity of these impacts can be influenced by management practices. Thus, it may be that the very long-term enhancement of low flows was due to the deep ploughing at this site, and modern practice currently prefers shallower cultivation drains. However, the very low permeability of the clay subsoil suggests that deep flows are likely to be extremely small, so that drain depth may have a limited hydrological importance. An experiment is being undertaken (T Nisbet, pers. comm.) to monitor the flows of drains of different depths to investigate this aspect. On a larger scale, foresters now prefer to have a mixed age forest structure for reasons including amenity and ecology. To these may be added the hydrological benefits since the impacts of forest disturbance such as ploughing will be diluted downstream by flows from other areas at different stages of forest development.

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